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Assessing the environmental impacts of renewable energy sources with emphasis on wind energy

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Abstract. Renewable energy (RE) technologies have become particularly popular worldwide, so as to mitigate climate change and to support addressing contemporary international energy market challenges. However, relevant projects may impact both the environment and humans. This study is based on a literature review of the environmental effects of RE projects. Wind energy, hydropower, solar energy and geothermal energy are the most common renewable energy sources. This review analyses environmental impact related data from, mainly, European countries, taking into account their commonality in Greece, considering relevant publications, articles, reports and papers with a time span of twenty-five years. This review's main objective is to identify and organize the environmental impacts during the different phases of a RE project, which are the pre-construction phase, the construction phase, the operation phase, the upgrade phase and the decommissioning phase. The environmental components used for an environmental impact assessment and the different receptor groups of each impact were taken into consideration, to properly map the environmental impacts. The study covers the natural and man-made environment affected by RE projects and emphasizes on wind energy projects. Main research gaps are highlighted, and future research steps are proposed.

1. Introduction

Renewable energy sources (RES) are an effective solution for mitigating climate change, reducing the dependency on fossil fuels and providing energy services in a sustainable way. RE technologies have numerous ecological, social and economic benefits, as they contribute to the reduction of greenhouse gas emissions, but also to local socio-economic development [1, 2]

Despite their numerous advantages, RE projects cannot be developed without environmental compromises and without considering public opinion and acceptance [3, 4]. Habitat fragmentation and disturbances, aesthetic impacts, soil erosion, land use changes are some of the environmental impacts of RE projects. Any anthropogenic structure affects the natural and the man-made environment. Therefore, all relevant environmental impacts must be identified, and special design and consideration is required, in order to mitigate them [5-7].

This review aims to identify the environmental impacts of RE projects in Europe, taking also into account their commonality in Greece. For this purpose, projects related to the following RES are investigated: wind energy, hydropower, solar energy and geothermal energy. Specifically, the objectives of this review are: (i) to identify and summarize, in a matrix form, environmental impacts mentioned in the literature, for every phase of the above RE projects, (ii) to classify these impacts according to the environmental components used for relevant impact assessment studies, (iii) to associate these impacts



with the affected receptor groups, and finally, (iv) to recommend future research considering the current knowledge gaps.

2. Materials and methods

This study is a modified systematic literature review, which was conducted following the main principles of the PRISMA 2020 guideline [8] and consists of two main parts: the first one includes the publications search and collection, and the second one the content analysis.

Regarding the first part, the first step involves the search of various types of publications, such as books, researches, studies, reports, papers and articles. Grey and scientific literature in English and Greek language was considered, mainly from European countries. Google, Google Scholar, Scopus, the official website of the Hellenic Ministry of Environment and Energy and the official website of the Library & Information Centre of the Aristotle University of Thessaloniki were selected as leading search platforms, using the keywords included in table 1 in a combined way, in order to conduct a thorough literature research. This procedure did not include all the possible combinations, but the research terms combinations were formed based on the relevant results, taking into account the thematic relevance of the keywords used. For example, the combination of the terms “ground source heat pump” and “shadow flicker” would not result in relevant literature, as the first one is related to geothermal energy and the second one to wind energy, so it was not included in the analysis. This also means that works and projects that make use of a combination of RE technologies were not included as such, but rather individual RE technologies were considered.

Table 1. Keywords - Search terms. A detailed explanation of each keyword - search term is provided in [9].

Greek search terms:	«ΑΠΕ», «ανανεώσιμες πηγές ενέργειας», «αιολική ενέργεια», «ανεμογεννήτριες», «χερσαία αιολικά πάρκα», «υπεράκτια αιολικά πάρκα», «υδροηλεκτρική ενέργεια», «υδροηλεκτρικοί σταθμοί ροής ποταμού», «φράγμα», «ηλιακή ενέργεια», «θερμικά ηλιακά συστήματα», «φωτοβολταϊκά συστήματα», «φωτοβολταϊκό πάρκο», «ηλιακή θέρμανση και ψύξη», «ηλιακός θερμοσίφωνας», «συγκεντρωτικά ηλιακά συστήματα», «γεωθερμική ενέργεια», «γεωθερμικά συστήματα», «αντλίες θερμότητας εδάφους», «αβαθής γεωθερμία», «γεωθερμία άμεσης χρήσης», «εξελιγμένα γεωθερμικά συστήματα».
Combined with:	«μελέτη περιβαλλοντικών επιπτώσεων», «περιβαλλοντικές επιπτώσεις», «βιοποικιλότητα», «οικότοποι», «φυσικό περιβάλλον», «πηγάδα», «φυσικό τοπίο», «χλωρίδα», «πανίδα», «μορφολογία του εδάφους», «κοινωνικο-οικονομικά», «ατμόσφαιρα», «θόρυβος», «ύδατα», «πολιτιστικό περιβάλλον», «αισθητική όχληση», «ανθρώπινη υγεία», «χρήση γης».
English search terms:	“RES”, “renewable energy sources”, “wind power”, “wind energy”, “wind turbines”, “onshore wind farms”, “offshore wind farms”, “hydropower”, “hydroelectric power plants”, “run-of-river hydropower”, “dam”, “wire”, “solar energy”, “solar energy systems”, “solar power plants”, “solar photovoltaic systems”, “solar heating and cooling”, “thermosiphon solar water heater”, “concentrated solar power”, “csp”, “geothermal energy”, “geothermal power plants”, “ground source heat pump”, “GSHP”, “direct use geothermal systems”, “enhanced geothermal systems”, “EGS”.
Combined with:	“environmental impact assessment”, “environmental impact”, “biodiversity”, “habitats”, “marine environment”, “wildlife”, “terrestrial mammals”, “birds”, “bats”, “landscape”, “flora”, “fauna”, “soil”, “morphology”, “social impacts”, “air quality”, “noise”, “water”, “historic environment”, “aesthetic impact”, “shadow flicker”, “human impacts”, “health impacts”, “land use”.

The literature search was limited to the relevant scientific areas, which are environmental studies, environmental engineering and environmental science. A twenty-five-year time frame was set in order to limit the number of publications. In this regard, the oldest study taken into account appeared in 1997, while the newest in 2022. During this process a large number of publications was identified. After that, the relevant literature was selected based on its content and non-relevant sources were excluded. The remaining publications were further examined with the aid of the criteria that were set. Those dealing with environmental impact assessment employing software tools and RE projects site selection were also excluded. After the screening process, additional publications were found by consulting the references list of each document, leading to a total of 80 relevant publications that were finally included in this review and represented in a table form [9].

Regarding the second part, i.e. the content analysis, the most significant impacts on the natural and anthropogenic environment for RE projects were identified via a thorough analysis of the collected literature [9]. For the identification of the environmental impacts, we took into account the five main phases related to the materialization of a typical RE-oriented project [10-12]:

- The pre-construction phase which includes activities such as land clearance, pre-engineering investigation, hydrological and meteorological studies, site investigation, geological and geotechnical surveys, initial environmental studies, mapping activities, securing approvals and permitting processes.
- The construction phase which includes activities such as material transport, the construction of the main structures and other components of the project, such as power transmission lines, access roads, substations and power generation main structures.
- Operation phase (which includes also maintenance), with activities related to the accessibility of the project, ordinary checks, service in case of technical problems etc.
- The repowering/upgrading phase which includes expanding and improving the project's facilities.
- The decommissioning phase which includes activities such as the demolition of all or some parts of the power generation facilities, as well as material management (e.g. storage, reuse, resale or disposal) and transport.

The environmental impacts were organized based on the matrix method [9]. The first column of the table of the impacts indicates the environmental components used for an environmental impact assessment, i.e. the components of the natural and anthropogenic environment, which include both biotic and abiotic features of the environment. The twelve environmental components used are the following [12, 13]:

- Aesthetics
- Acoustic environment, vibration, electromagnetic fields, radiation
- Human health
- Atmospheric environment
- Soils, morphology, geology, tectonics
- Surface and underground water
- Historic environment and cultural heritage
- Climate and bioclimate
- Socio-economic environment
- Residential environment
- Natural environment
- Land use

The second column of the table of impacts indicates the major receptor groups affected by each environmental impact. These groups are: the environment, humans, various species (mammals, amphibians and reptiles, invertebrates, plants and aquatic organisms), various marine species (plants, algae and invertebrates), marine mammals, marine habitats, bats, habitats, birds and fish.

3. Results and discussion

The conducted literature review suggests that storage hydropower plants have the highest number of environmental impacts (74), followed by run-of-river hydropower (71), offshore wind farms (67), onshore wind farms (60), photovoltaics and concentrating solar power (40), enhanced geothermal systems (35), direct use geothermal (19), solar heating and cooling (9) and ground source heat pumps (6). All results reported and discussed are based on the aforementioned review and therefore reflect the information and conclusions reported in the specific set of literature that resulted from the specific analysis.

Based on the above, the natural environment appears to be the most affected environmental component in most RE projects (storage hydropower, run-of-river hydropower, offshore wind farms, onshore wind farms, photovoltaics and concentrating solar power), as shown in figure 1. To be more specific, onshore wind farms' impacts appear in every environmental component, while many of them appear in the socio-economic environment and human health as well. In addition, offshore wind farms are reported to affect the natural environment at the highest level among all projects. Such wind farms are not expected to have any interaction with the residential environment, but they appear to have multiple impacts on the acoustic environment, to cause vibration-related problems, to have an influence on electromagnetic fields and radiation and to affect the socio-economic environment as well. Hydropower projects (run-of-river and storage) have been found to interact with all the environmental components and to have a significant number of impacts on surface and underground water and the socio-economic environment as well. As for the solar energy projects, photovoltaic and concentrated solar power (csp) systems' impacts appear in relation to historic environment and cultural heritage. On the other hand, solar heating and cooling systems' impacts are reported to influence seven out of the twelve environmental components addressed. Regarding the geothermal energy systems, the impacts of ground source heat pumps are reported to have an influence on four out of the twelve environmental components, while direct use geothermal technologies' impacts influence more environmental components (ten out of the twelve accessed). Finally, the impacts of the enhanced geothermal systems are reported to affect all twelve environmental components, with the highest degree of influence appearing for the socio-economic and natural environment and for surface and underground water.

Moving on to the impacts on each receptor group (figure 2), humans appear to be the most affected receptor group in the case of onshore wind farm projects, followed by habitats, birds and bats, the environment in general and various species. Offshore wind farms have been found to affect most of the receptor groups among all RE projects, while it is the only project type for which influences are reported for the receptors of the marine environment. The only receptors that are not affected by offshore wind farms are the habitats and the various in-land species. The most frequently affected receptor group is reported to be humans. The hydropower projects studied appear to have almost the same number of impacts for every receptor group. Specifically, habitats are affected by these projects at the highest level, followed by humans, fish, the environment, various species and birds. As for the solar energy projects, photovoltaic systems seem to influence all the receptor groups, apart from the ones of the marine environment. In addition, csp systems have most of their impacts on habitats, whereas solar heating and cooling affect two receptor groups, the environment and humans. Finally, ground source heat pumps appear to have only a few impacts on habitats, the environment and humans. On the other hand, enhanced geothermal systems and direct use geothermal systems seem to influence humans, the environment, habitats and various species. Generally, the environment and humans are the only receptors that appear to be affected by all projects, but many projects are found to have impacts on habitats, various in-land species and birds as well.

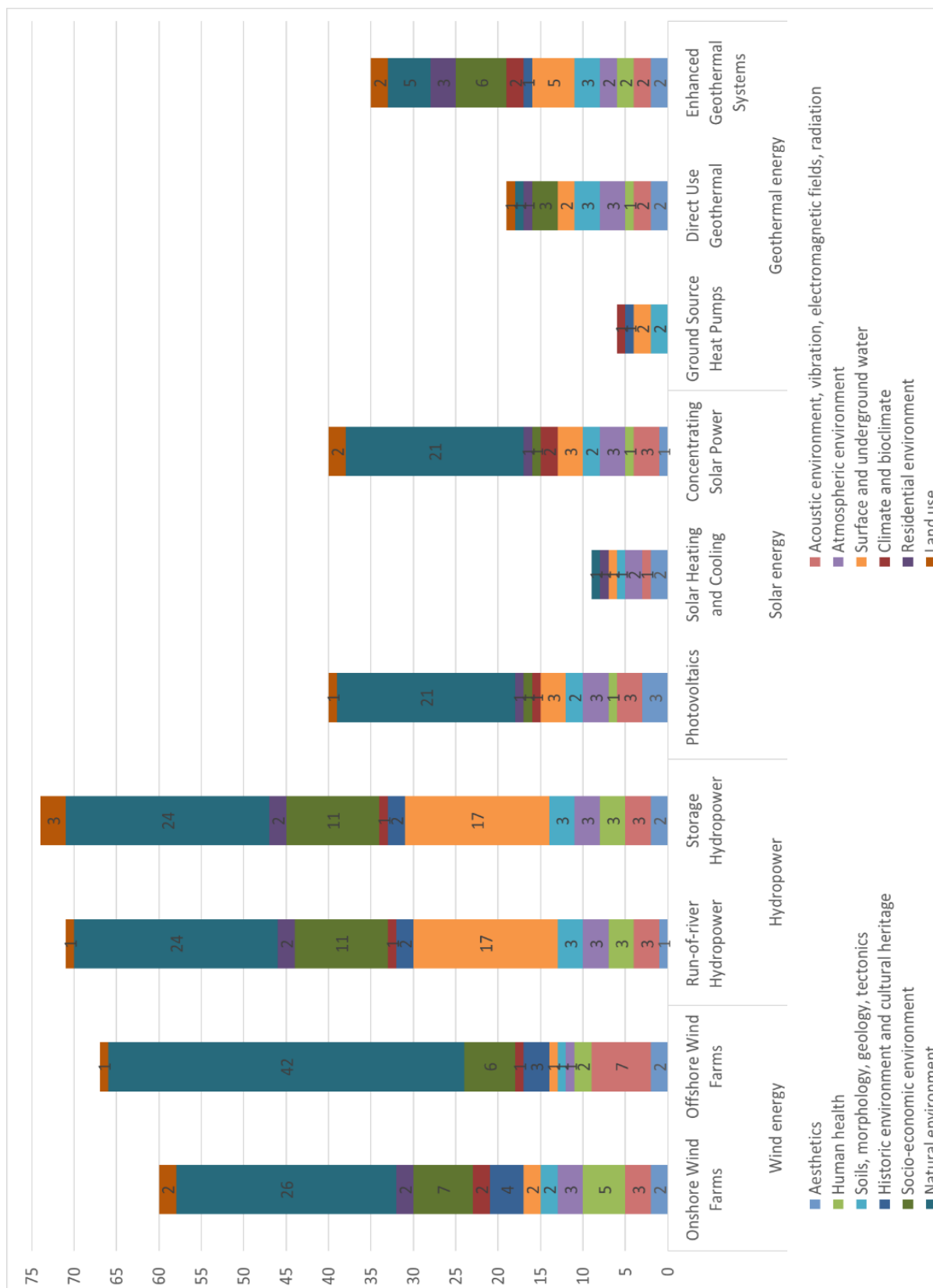


Figure 1. Distribution of impacts on each environmental component by RE project.

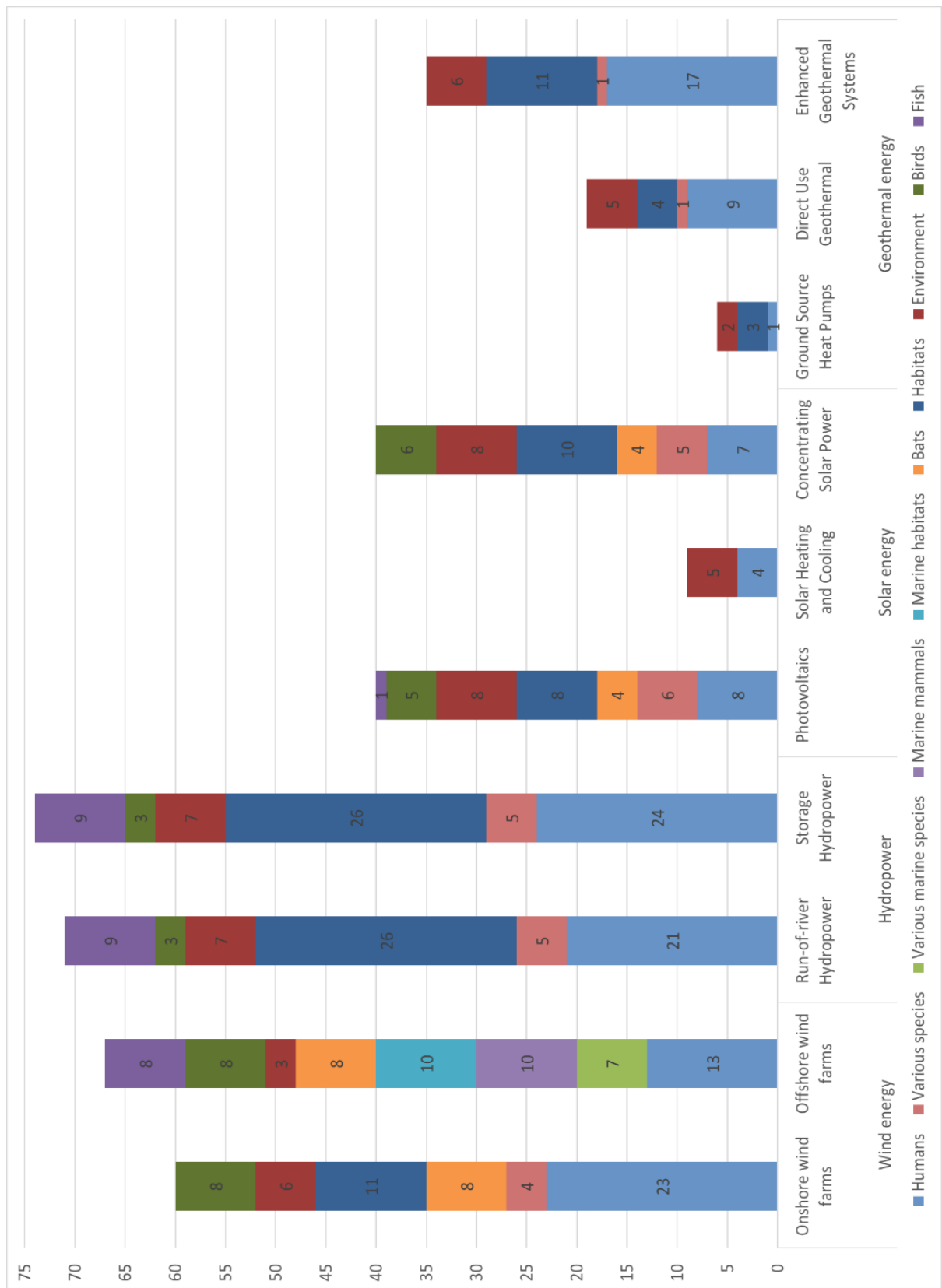


Figure 2. Distribution of impacts on each receptor group by RE project.

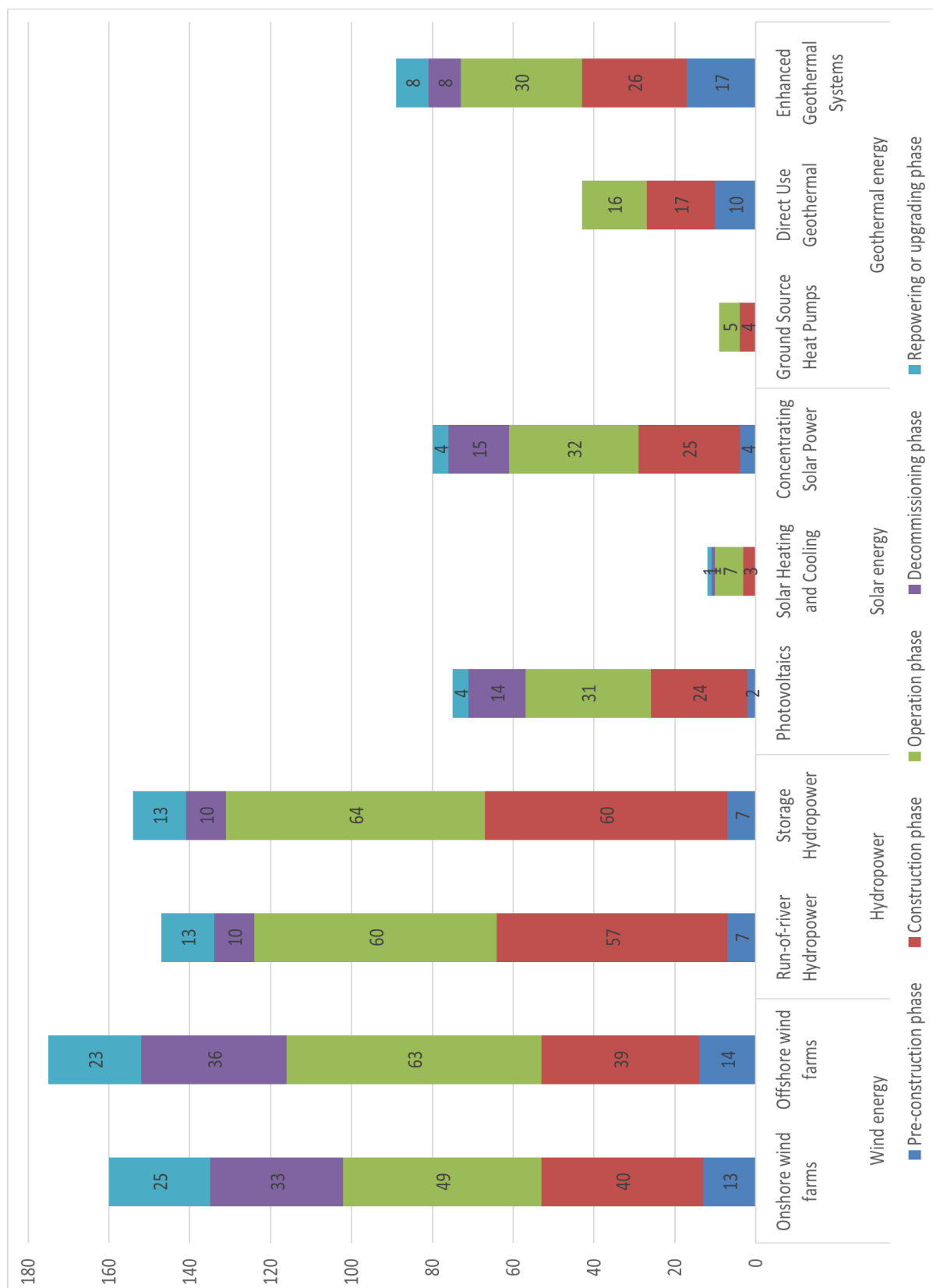


Figure 3. Distribution of impacts for each project phase and by RE project

As for the distribution of impacts on each project phase (figure 3), most impacts of all projects are found during the operation and the construction phases. Wind energy projects, in particular, appear to have a significant number of impacts during decommissioning and repowering/upgrading phases and fewer during the preconstruction phase. Hydropower projects on the other hand seem to have very few impacts during the pre-construction, decommissioning and repowering/upgrading phases in comparison with the ones during the operation and the construction phase. A significant number of impacts is reported for photovoltaic and csp systems during the decommissioning phase. In contrast, much fewer impacts are reported for the same type of projects concerning the pre-construction and repowering/upgrading phases. Solar heating and cooling project impacts are reported during operation, construction and repowering/upgrading phases. Among all the geothermal energy projects, only enhanced geothermal systems have impacts during all phases, while ground source pumps' impacts appear only during operation and construction and direct use geothermal systems' also during the pre-construction phase. In general, impacts during pre-construction, decommissioning and repowering/upgrading phases, are found to be the less investigated in the studied literature.

4. Conclusions

This study intends to give an overview of the environmental impacts caused during the different phases of RE projects, on the basis of a systematic literature review. It also intends to organize them taking into consideration the environmental components addressed for environmental impact assessments and the different receptor groups affected by each impact. The RE projects studied are the most common in Greece, i.e. wind, solar, hydroelectric and geothermal energy projects. The impacts of these projects were identified taking into account the five phases of RE projects, which are pre-construction, construction, operation, repowering or upgrading and decommissioning phase. The environmental components and receptor groups, that are used to organize the environmental impacts, cover the natural and man-made environment.

Results suggest that the most investigated component when it comes to RE project environmental impacts is the natural environment, while the less investigated one is the residential environment. Hydropower and wind energy projects were found to exhibit the highest number of impacts, with the storage hydropower occupying the first place among all RE projects (pre-construction), while solar and geothermal energy projects the last (decommissioning). The results of the further analysis conducted concerning the distribution of impacts on each project phase, on each environmental component and on each receptor group, suggests that most of the impacts (for all projects) occur during the construction and the operation phases. The natural environment is found to be the most affected component, and humans and habitats are in parallel reported as the most affected receptors in the majority of RE projects. In general, the environmental components and receptor groups that are affected every time, depend on the phase of the project and the RE project nature itself.

This paper investigates the impacts of RE projects only in their five predefined phases. In order to make a more comprehensive assessment of the environmental impacts of these projects, a life cycle analysis approach is suggested, which may allow us to identify the impacts on every stage of the lifecycle of a RE project. During this process, the contribution of RES in climate change mitigation should be considered and compared to the conventional energy sources.

Furthermore, all projects do not have the same impacts or to the same extent. Therefore, a new research should be conducted in order to quantify and determine the importance of each impact and finally prioritize the impacts of each RE project.

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